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PRACTICAL EXPERIENCE WITH THE CAPILLARY ELECTROMETER.

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The Capillary Electrometer is an instrument whose merits are not generally appreciated either by teachers of physics or by those engaged in research. Though it is now nearly thirty years since the original form of the instrument was first described by Lippmann,[1] few laboratories contain one today.

His paper gives a careful study of the capillary electrometer and the principles upon which its operation depends, but he failed to give it a convenient form for either laboratory or research purposes, a fact which perhaps explains the neglect it has received. Siemens[2] a little later describes a modification especially designed to replace the reflecting galvanometer for electrical measurements on shipboard, a use to which its indifference to mechanical vibrations well adapts it. Quincke,[3] Gore and later Paschen[4] have published careful studies of the instrument. Its merits have been emphasized and brought to the attention of certain classes of workers, especially by Ostwald in Germany and recently by Burch in England. Ostwald[5] recommends it strongly for work in physical chemistry and Burch[6] shows its special value for physiologists and electrical engineers.

My attention was directed to the capillary electrometer by

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[1] Lippmann. *Pogg. Annalen*, Vol. 149, p. 546 (1873).

[2] Siemens. Pogg. Ann., Vol. 151, p. 639 (1874).

[3] Quincke. Pogg. Ann., Vol. 153.

[4] Paschen. Wied. Ann., Vol. 39, p. 43 (1893).

[5] Ostwald. Zeit. f. phys. Chem., Vol. 1, p. 404 (1887). See also his book "Hand-und-Hilfsbuch zur Ausführung Physiko-chemischer Messungen" p. 242–249.

[6] Burch. London Electrician, Vol. 37, p. 380, 401, 435, 473, 514, 532 (1896).

the volume of Ostwald. It struck me that it ought to be a first rate instrument for use in the physical laboratory for a great variety of purposes. An experience of several years, which includes a study of its practical fitness for use in measurements usually made with costly electrometers and galvanometers, has strengthened that first impression. Among the advantages which may be fairly claimed for the capillary electrometer are the following:

1. It is wholly unaffected by any magnetic disturbances in its neighborhood and far less sensitive to mechanical vibrations than any galvanometer or electrometer of equal sensitiveness. So it is possible to use it in the immediate vicinity of powerful dynamos or electromagnets.

2. It far excels any other forms of electrometer, whether of attracted-disc or quadrant type, in sensitiveness. It can be made to show .00001 volt and easily measures .0001 volt. It is also much more free from disturbance by accidental electrostatic changes in the neighborhood than is a quadrant electrometer.

3. It is extremely dead beat, the setting of the instrument requiring only a very small fraction of a second.

4. It is so sensitive that it may replace a high-resistance reflecting galvanometer for many purposes, and with the great advantage, that it takes no current at all from the circuit being measured.

5. It is much smaller, lighter, more portable, more easily and quickly set up—in general more convenient—than any other form of electrometer.

6. It is cheap and readily constructed by the experimenter for himself. It is indeed almost ridiculously cheap in the simplest form. A capillary electrometer costing a dime for materials and a half hour's labor will excel a $250 quadrant electrometer in sensitiveness. Enough of them can be quickly prepared for the use of a large class of students at a nominal cost.

7. The extreme quickness with which it follows fluctuations in potential difference enables it to do some things that

no ordinary form of electrometer or galvanometer can do, as for example, give an instantaneous record photographically of the variations of E. M. F. or current through one or more cycles of an alternating-current dynamo.

My own experience with the capillary electrometer began with the three forms described by Ostwald in the volume already cited. Figures 1, 2 and 3 (Plate LXII) will serve to recall their construction, without detailed description. The instrument consists essentially of two small bodies of mercury separated from each other by sulphuric acid. In each figure:

b is a glass tube of perhaps .5 cm. diameter, one end of which is reduced to capillary dimensions, and which contains mercury electrically connected to one terminal of the instrument.

c is a larger tube or bulb of perhaps 1 cm. diameter, containing the other body of mercury, attached to the second terminal of the instrument. Connection between *b* and *c* is made by

a, the capillary within which mercury and acid come in contact.

e is the anode terminal.

I have made and used about twenty instruments of these three types. The first form is very convenient and sensitive enough for many laboratory experiments. The one I have used most gives about one scale division (about 1 mm.) for .01 volt potential difference, but by using a smaller capillary this type can be made three or four times as sensitive.

The second form is altogether better than the first and is used in connection with a cheap reading microscope to magnify its small deflections. It is an excellent form—the best of the three Ostwald describes—for general laboratory use. The ones that I have used most give a deflection of 14 to 35 divisions on the rotating head of a certain micrometer microscope, 1960 of whose divisions equal one millimeter. In this type it is better to have the terminal platinum wires sealed into the glass at *b* and *c*. (Fig. 2).

The third form is decidedly more sensitive, but is far less convenient to use and gets out of order more easily—so easily indeed that only skilled experimenters can use it with

satisfaction. High sensitiveness requires a very fine capillary, of perhaps .02 mm. diameter. So fine a capillary is easily clogged by a minute particle or breaks develop in the mercury column which hours of labor sometimes fail to remove. I have had one which showed a deflection with .00005 volt; another moved 1-5 mm. (375 divisions on micrometer head) with a potential difference of .001 volt. But neither of these remained long in good working condition.

A series of nerve-trying experiences with Ostwald's third type led me to seek some modification which would be highly sensitive and at the same time keep in working order fairly well and be capable of restoration to a sensitive condition if by chance injured through misuse. This was found at length in a modification of a simple form described by Paschen. On reading his paper (Wied. Ann. Vol. 39, p. 43) I noticed that he reached a fair degree of sensitiveness in a form of instrument in which the capillary, (if such it can be called) was of relatively huge dimensions (3 mm. in diameter). His arrangement is shown in Fig. 4. The capillary is one of the limbs of a U-tube. In his instrument one limb was 24 mm. in diameter the other three. As the sensitiveness of the Lippmann and Ostwald forms is nearly inversely proportional to the size of the capillary, it was natural to suspect that a reduction in size of the smaller limb to moderate capillary dimensions would exalt the sensitiveness sufficiently and still avoid the exasperating tendency to clog and stick that inheres in Lippmann's or Ostwald's third form. This proved to be the case.

A number of Paschen instruments were constructed with capillary limbs of varying size. One similar in dimensions to his gave rather low sensitiveness, but as the capillary was made smaller the sensitiveness increased as shown by the following table:

Tube	*Diam. of Capillary*	*Deflection for .001 volt*	
1	3.70 mm.	.0018 mm.=	3.6 divisions
2	1.32	.0038	7.3
3	1.05	.0092	18.
4	.51	.0117	23.
5	.31	.0255	50.
6	.21	.0765	150.
7	.16	.0260	51.

In observing the deflections a microscope with eyepiece micrometer was used, 1960 of whose divisions on the rotating head are equal to 1 mm.

Thus the hope of securing high sensitiveness with this form was realized. Tube 1 was of nearly the same size as that used by Paschen, while tube 6 with a capillary of about one-fifth millimeter, showed a sensitiveness more than 40 times as great. (It should be mentioned in this connection that sensitiveness was not an object in Paschen's research, but it was necessary to have the capillary of large size in order to allow the gas formed by the high voltages used, to escape.)

The most surprising feature of the above table is the indication of maximum sensitiveness for a capillary of about one-fifth millimeter diameter. The extreme sensitiveness of tube No. 6 is however probably due in part to its form, for another of nearly the same diameter but of somewhat different taper gave a deflection only one-third as great. A number of observers have called attention to the influence of the shape of the capillary tip in instruments of Ostwalds third form, and many of my own measurements show it.

No. 6 not only shows great sensitiveness, but (in sharp contrast with those of similar delicacy of the ordinary type) does not easily get out of order and can be taken apart, washed and dried, and show its former sensitiveness when set up anew. To test its durability and constancy under such conditions, the following course was adopted. After its sensitiveness had been measured, it was short circuited, and the next day its constant was redetermined. It was found unchanged. Another wait of two days showed its sensitiveness slightly increased. Several weeks later it was taken apart, washed and shipped to a neighboring state. After eight months it was again set up with different mercury and acid, and the sensitiveness when measured was found to be nearly the same as before.

The resemblance of this type to Ostwald's second form is rather close. The shorter length of its capillary is a considerable advantage however, provided the capillary is fine. Breaking or clogging of the mercury column is less likely to occur

and friction is reduced. It is also much more readily cleaned than the other, if occasion should arise. Further, it is much more difficult to blow an instrument of Ostwald's second form, if the capillary is smaller than .5 mm. But the modified Paschen type is readily made with a capillary as small as .2 mm. with a gain in sensitiveness about six fold.

Comparing the best of the latter type with about ten electrometers of Ostwald's third form, I found it three times as sensitive as the best of them. It was exceeded in sensitiveness, it is true, by one of them but this one maintained a useful life only one hour long. A partial determination of its sensitiveness was hardly completed when it suddenly stuck. Two days were wasted in an unsuccessful attempt to wash, dry and refill its capillary. The mercury could not be again forced through it. Its diameter did not much exceed .01 mm. (as against .21 in the Paschen). Such experiences with very sensitive electrometers of the Ostwald third type are not uncommon. The larger capillary in the other instrument prevents this difficulty.

Figure 5 shows the construction of the modified Paschen form, as exhibited by the instrument before referred to as "No. 6." The letters a, b, c, etc., designate the same parts as in the other figures. To give an idea of the dimensions the following will suffice: Internal diameter of capillary *a* .21 mm., of tube *b* 8.2 mm., of the outer containing tube 16 mm. The mercury stands 39 mm. higher in *b* than in *a*. The capillary *a* is drawn down from a thick walled capillary of 2 mm. internal diameter, fused on to the drawn-out end of the large tube *b* in the blast lamp and finally bent into the U-shape by cautiously holding it in the edge of a small Bunsen flame. A sealed-in platinum wire leads from the mercury at *c* to the anode *e*. A paraffined cork (slit to keep it from fitting air tight) serves to support *b* firmly with the capillary close to the wall of the outer tube, also to prevent evaporation or spilling of the dilute acid. Another cork in *b* prevents loss of mercury, keeps out dirt and supports the other terminal wire. The whole is supported by a base of dry, varnished wood.

Some measurements were made to determine the influence

on the result of the size of the other limb of the U-tube and also that of the anode surface. To examine the first point a set of three U-tubes was prepared, whose capillary limbs were made from the same piece of uniform thermometer tubing of 1.05 mm. inside diameter. The other limbs measured 3.7, 8 and 12.2 mm. respectively in diameter. They were found to compare in sensitiveness in the ratio of 10 : 18 : 18.4. This indicates that the size of the larger limb is of some importance. It should not be much less than 10 mm., but there is little advantage in making it larger than that. In Paschen's original instrument it measured 24 mm. The large surface of the mercury anode was another peculiarity of his instrument. Following him I at first used an anode surface 62 mm. in diameter. Replacing this by one of 39 mm. made no measurable difference in the sensitiveness.

Practical experience emphasizes the importance of some cautions given by Ostwald and by Burch in the references cited. In particular :

a). Good insulation must be provided.

b). The terminals must be kept short-circuited through a conductor except during the momentary and occasional pressure of a key in taking a reading. Ostwald's short-circuiting key is satisfactory.

c). The acid strength may be considerably varied, say from 1 to 3 up to 1 to 20 by volume. Results are somewhat irregular if the acid is as weak as 1 to 25.

d). Hydrochloric acid is not satisfactory.

e). A new instrument will usually be irregular, and will "crawl" with the key between stops until its terminals have been short-circuited for a day or so.

f). In using the instrument, avoid anodic polarization of the capillary as much as possible. Try to keep it the kathode. The ill effects of too much anodic polarization can be partly remedied by electrolysis.

Several novel forms of capillary electrometer were constructed in connection with the present study. One was suggested by the extraordinary electro-capillary engine described

by Lippmann in the paper cited. It consisted of a cylindrical bundle of about 200 capillary tubes, each 20 mm. long and 1 mm. in diameter, bound around a glass rod with fine platinum wire. This was allowed to rest upon a surface of mercury contained in a small glass vessel. The whole was immersed in dilute sulphuric acid in a larger vessel, with enough mercury to cover the bottom. The glass rod was attached to the short arm of a long lever supported on a knife edge fulcrum. The long arm was made very light, 120 cm. in length. It carries a glass scale divided to .1 mm. at its end. When the two mercury surfaces are brought to a different potential the bundle of capillaries rises or falls and with it the lever moves and the divided scale is observed with a low-power microscope. It showed a distinct movement with a potential difference of .0001 volt. With .1 volt, the movement of the big lever was quite impressive. By replacing the lever with a small mirror and reflecting sunlight across the room, the capillary movement might be shown to a large audience.

Another instrument has a separate pressure apparatus with a flexible tube connected to a mercury reservoir capable of being raised and lowered. This is used in connection with a capillary tip of Ostwald's third form, very much as suggested by Burch in the London Electrician articles.

At the suggestion of Prof. Stratton of the University of Chicago, I attempted to replace the lever arrangement of the capillary-bundle form by a pair of plane parallel plates, one being fixed and the other attached to the bundle of tubes, the movement of the latter to be estimated by the movement of interference bands across the plate when the arrangement was illuminated by sodium light. I got some results with this, but my mechanical arrangements were so imperfect that the requisite degree of parallelism of the plates could not be long maintained.

Several forms were made particularly for projection with the lantern, but Ostwald's second form was found to be as good for projection as any of the special ones. It can be very satisfactorily shown on the screen.

To sum up briefly the comparison of leading types of the instrument used: For general use in laboratory instruction and for projection Ostwald's second form is to be preferred. This can be made sensitive to about .0001 volt and is useful for such work as determining resistance by the fall-of-potential method, E. M. F. by comparison with a standard cell, current by the potentiometer, etc. Ostwald's first form may be substituted where the cost of the reading microscope used with the second type is an item of importance, but the superior sensitiveness of the second form recommends it.

For higher sensitiveness, in research work or very exact laboratory measurements, the modified Paschen electrometer with capillary about .2 mm. in diameter is highly satisfactory and better than Ostwald's third form.

The experimental work described in this paper was done at the University of Chicago and at Denison University.

Ohio State University.

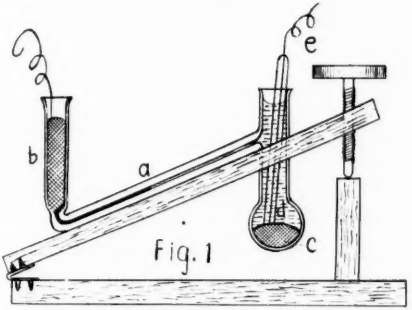

Fig. 1

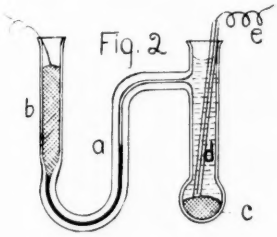

Fig. 2

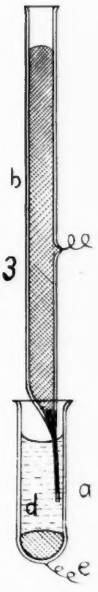

Fig. 3

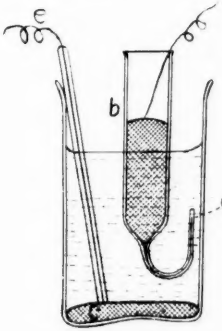

Fig. 4

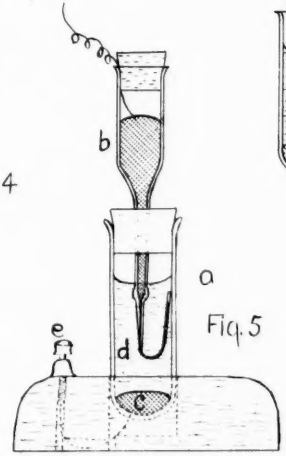

Fig. 5